Compaction of diagenetically altered mudstones – Part 2: Implications for pore pressure estimation

N.R. Goulty*, C. Sargent

Department of Earth Sciences, Durham University, South Road, Durham DH1 3LE, UK

*Corresponding author.

E-mail address: n.r.goulty@durham.ac.uk (Neil Goulty).

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Abstract

Diagenetically altered mudstones compact mechanically and chemically. Consequently, their normal compaction trends depend upon their temperature history as well as on the maximum effective stress they have experienced. A further complication is that mudstones are commonly overpressured where clay diagenesis occurs, preventing direct observation of the hydrostatic normal compaction trend. A popular way to estimate pore pressure in these circumstances is to calculate the sonic normal compaction trend in a well with a known pressure–depth profile by applying Eaton's method in reverse, and then to estimate pore pressure in offset wells using Eaton's method conventionally. We tested this procedure for Cretaceous mudstones at Haltenbanken. The results were inconsistent because the sonic log responds differently to disequilibrium compaction overpressure and unloading overpressure, and their relative contributions vary across the basin. In theory, a two-step method using the density and sonic logs could estimate the contributions to overpressure from disequilibrium compaction and unloading. The normal compaction trend for density should be the normal compaction trend at the maximum effective stress the mudstones have experienced, not at hydrostatic effective stress. We advocate the Budge-Fudge approach as a starting point for pore pressure estimation in diagenetically altered mudstones, a two-step method that requires geological input to help estimate the overpressure contribution from disequilibrium compaction. In principle, the Budge-Fudge approach could be used to estimate the normal compaction trend for mudstones at the maximum effective stress they have experienced, and so form the basis of the full two-step method through the use of offset wells. Our initial efforts to implement the full two-step method in this way at Haltenbanken produced inconsistent results with fluctuations in estimated pore pressure reflecting some of the fluctuations in the density logs. We suspect that variations in the mineralogical composition of the mudstones are responsible.

Keywords: Mudstone; Pore pressure; Clay diagenesis; Normal compaction; Disequilibrium compaction; Unloading; Budge-Fudge; Eaton

Highlights

- We introduce the normal compaction surface for diagenetically altered mudstones.
- Eaton's method gives poor results where overpressure generation mechanisms vary.
- Separate accounting for disequilibrium compaction and unloading is required.
- In principle, a two-step method can be implemented using density and sonic logs.
- The Budge-Fudge approach offers a partial solution and basis for a two-step method.

1. Introduction

This article and its companion article, Part 1 (Goulty et al., 2016), are directed towards improved pore pressure estimation using wireline logs in mudstones at the temperatures where clay diagenesis takes place. In Part 1, we show that mechanical and chemical compaction have both continued to take place in Cretaceous mudstones at Haltenbanken, offshore mid-Norway up to temperatures of at least 130 ^{o}C. In this article, we examine the implications for pore pressure estimation.

A description of the geology is given in Part 1, based on the work of Blystad et al. (1995) and Dalland et al. (1998). Here we repeat only the key points. Following a Jurassic–Early Jurassic rift episode, the Cretaceous post-rift sediments at Haltenbanken were deposited in a moderately deepwater marine environment. The Lower Cretaceous Lange Formation and the overlying Upper Cretaceous Kvitnos Formation comprise our study interval, and have a combined thickness of up to 1800 m. Their lithology is mainly mudstone, although there are several isolated sandstone turbidites in the upper part of the Lange Formation. They are overlain by around 1200 m thickness of Upper Cretaceous–Neogene claystone formations, terminating at an unconformity that developed during the late Pliocene. Since 2.8 Ma, following the late Pliocene hiatus, burial has been rapid as glaciogenic sediments of the Naust Formation were deposited with thickness ranging up to 1300 m in the study area (Rise et al., 2005).

The Cretaceous mudstones in the Haltenbanken area lie at depths where temperatures are in the range 70–170 °C. The sparse pressure data available in the Cretaceous formations show that the pore pressure–depth profile is fairly consistent across the area (O'Connor et al., 2012), yet Cicchino et al. (2015) found wide differences in porosity between wells (Fig. 1). In Part 1, we analysed density and sonic logs to show that the effective stress history is the principal factor responsible for the porosity differences: at the same depth, the lower porosity mudstones in the northeast of the study area have experienced more mechanical compaction than the higher porosity mudstones in the southwest.

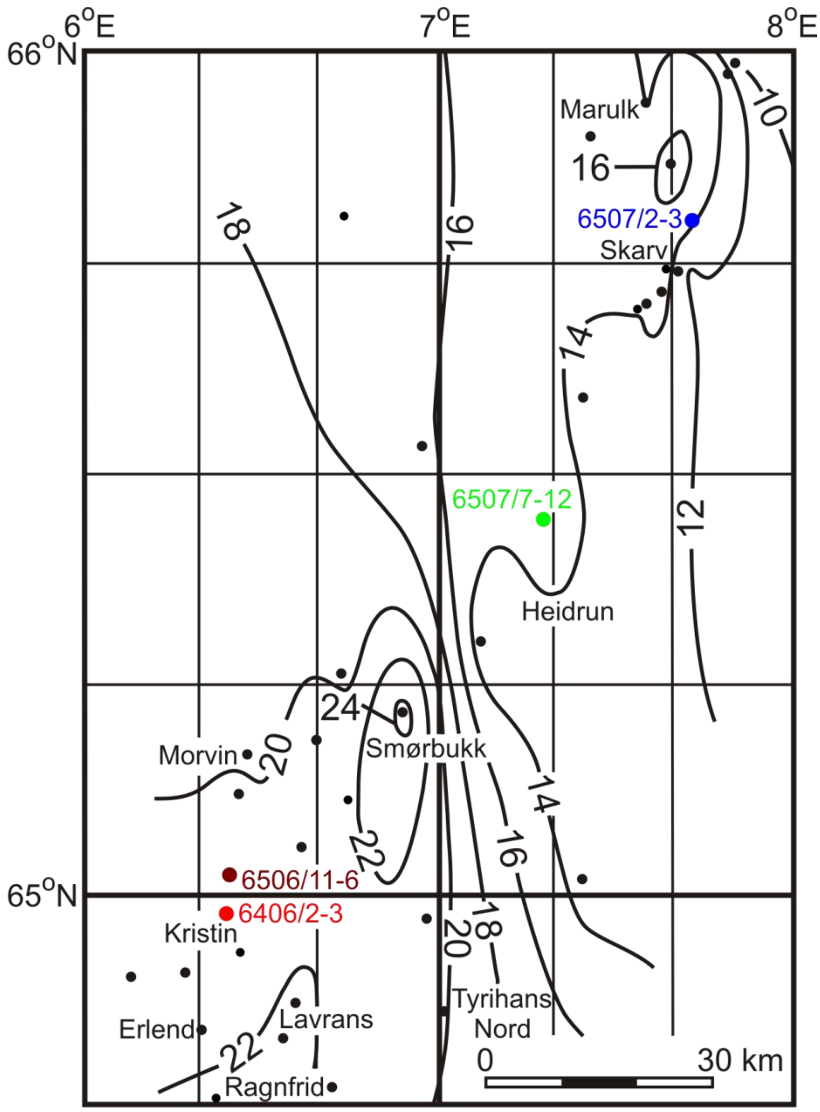

Fig. 1. Map of the study area with contours of the density log porosity values (%) on the best-fitting exponential trends for the Cretaceous Kvitnos and Lange mudstones at 2700 m depth below seafloor.

Here we introduce for diagenetically altered mudstones the concept of a normal compaction surface on a 3-D plot of vertical effective stress against sonic transit time and density, and point out that there is a corresponding unloading volume in this 3-D space. This plot helps us to visualize why the vertical effective stress is not uniquely defined by density and sonic transit time in diagenetically altered mudstones, even if their depositional lithology is known and they have been uniaxially consolidated. We then compare pore pressure estimates from wireline logs in the Cretaceous mudstones at Haltenbanken obtained by the widely used method of Eaton (1975) and the Budge-

Fudge approach proposed by Sargent et al. (2015). We argue that the Budge-Fudge approach is preferable because it requires explicit accounting for both disequilibrium compaction and unloading mechanisms of overpressure generation, although it does require geological input to help estimate the overpressure contribution from disequilibrium compaction. In principle, it should be possible to apply the Budge-Fudge approach in offset wells to provide the basis for a full two-step method of pore pressure estimation using density and sonic logs in a subject well.

2. Normal compaction surface and unloading volume

Normal compaction behaviour describes the porosity response of clastic sediment to increasing effective stress, without restriction to circumstances where the pore pressure remains hydrostatic. Commonly, only vertical effective stress is considered because it is relatively easy to determine, by integrating the density log. This simplification is valid for 1-D compaction or, more generally, in circumstances where the ratio between horizontal effective stresses and the vertical effective stress does not change with depth (Goulty, 2004).

A viable method of pore pressure estimation within mudstones in the mechanical compaction regime, at temperatures below 70 ^{o}C, is the equivalent depth method (e.g., Mouchet and Mitchell, 1989), in which porosity is assumed to be a single-valued function of vertical effective stress. The method accounts for overpressure generated by disequilibrium compaction, but not for overpressure generated by unloading, i.e., reduction in vertical effective stress, which may result from exhumation or overpressure generation by processes such as gas generation or lateral transfer. Goulty (2004) and Hauser et al. (2014) have suggested how the equivalent depth method could be refined to take account of tectonic stress by treating porosity as a function of mean effective stress and differential stress. These variations on the equivalent depth method are all appropriate where the mechanism of overpressure generation is disequilibrium compaction in response to loading. However, in diagenetically altered mudstones they are not viable because clay diagenesis makes mudstones more compactable (Lahann, 2002), shifting the normal compaction curve towards lower porosity for a given value of vertical effective stress.

Bowers (1995) recognized that the equivalent depth method needed to be supplemented to estimate the contributions to overpressure from both unloading and disequilibrium compaction. He later proposed that sonic and density log responses should be combined to estimate the separate contributions (Bowers, 2001). Normal compaction curves are required to define the relationships between sonic velocity and density, both proxies for porosity, and the vertical effective stress for mudstones that have not been unloaded.

On a 3-D plot of vertical effective stress against sonic transit time and density, the normal compaction trend for uniaxially consolidated mudstones of initially uniform lithology that are hydrostatically pressured is a curvilinear trajectory (Fig. 2a). Its projection onto the three coordinate planes gives the hydrostatic normal compaction trends for each pair of variables. The projection onto the horizontal sonic–density plane is shown as a straight line here, although we note that mudstones which are initially smectite-rich have a curvilinear trend on the crossplot of sonic transit time against density due to clay diagenesis (Fig. 3). If the vertical effective stress acting on a normally compacted mudstone is reduced, the trajectory on the 3-D plot follows an unloading path towards higher sonic transit time and very slightly lower density (Fig. 2b), as the flexible connecting pores open elastically (Bowers and Katsube, 2002). The continuum of unloading paths forms the unloading surface bounded by the normal compaction trend, as described by Goulty and Ramdhan (2012). Thus, Bowers (2001) suggested that values of sonic transit time and density in a mudstone should correspond to a single point on the unloading surface and determine the vertical effective stress unambiguously.

Bowers' (2001) method is appropriate for pore pressure estimation where the correct normal compaction curves relating sonic velocity and density to the maximum vertical effective stress experienced by the mudstones are those for hydrostatic pore pressure, as in the mechanical compaction regime, but it does not explicitly account for the point raised by Lahann (2002):

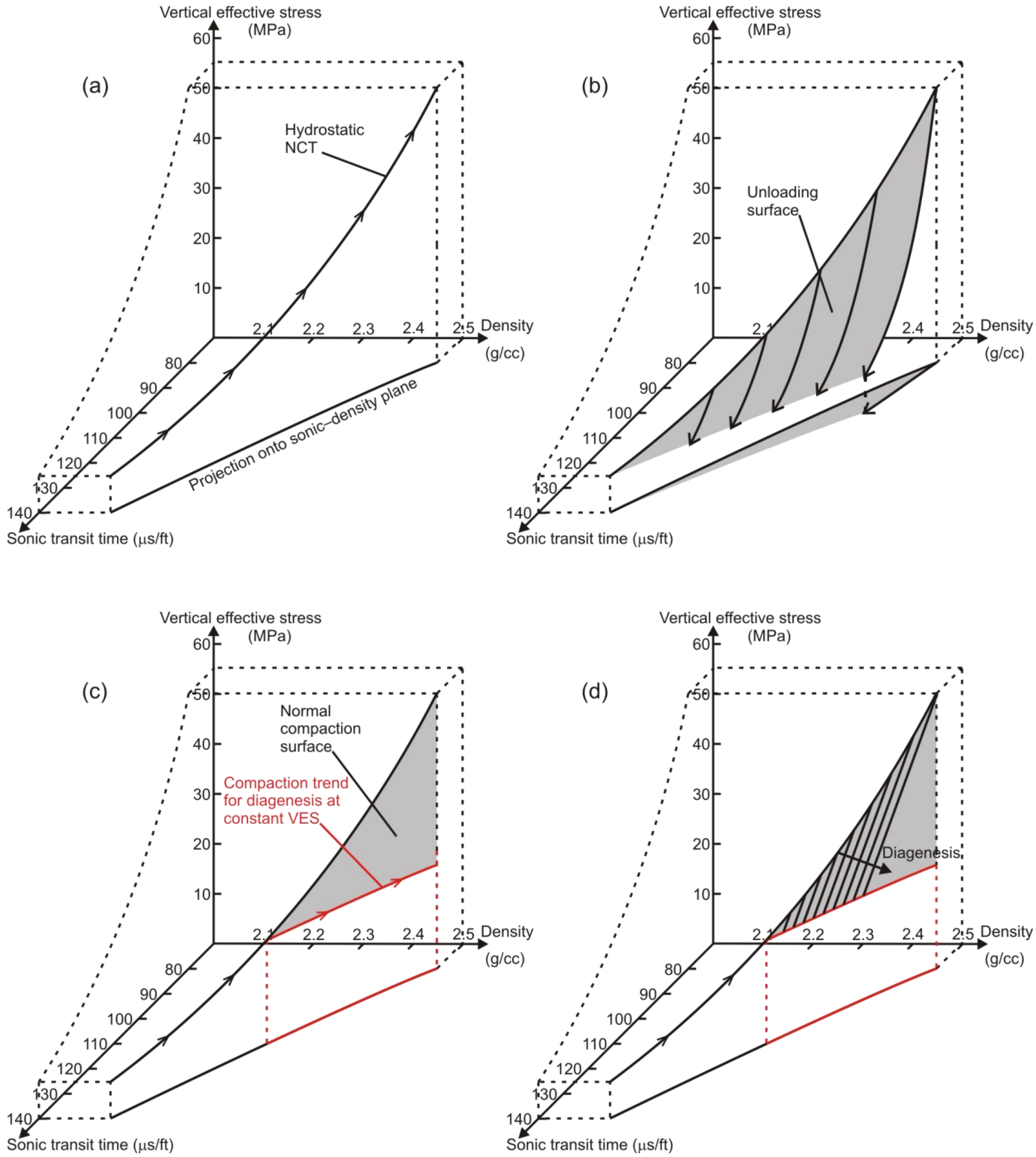

Fig. 2. Plots of sonic transit time, density, and vertical effective stress on three Cartesian axes. (a) Normal compaction trend (NCT) defining the relationship between sonic transit time, density and vertical effective stress when pore pressure is hydrostatic at all depths. (b) Unloading surface defined by the continuum of unloading curves starting from all points on the hydrostatic NCT. Projection of the unloading surface onto the horizontal plane shows where points may lie on the sonic-density crossplot. (c) Red arrowed curve is the NCT followed if the mudstone becomes partially sealed during burial such that the vertical effective stress is fixed at a particular constant value as clay diagenesis proceeds. (d) Normal compaction surface with contours for the degree of clay diagenesis. These contours extend as surfaces into the unloading volume (not drawn).

diagenesis makes mudstones more compactable, shifting normal compaction curves towards lower porosity and, therefore, towards higher density and sonic velocity, at constant vertical effective stress. Although the hydrostatic normal compaction trend for the mudstones in any well is unique, after the onset of diagenesis in a mudstone, at ~70 °C for smectite-to-illite transformation (Boles and Franks, 1979), there is chemical porosity loss as well as mechanical porosity loss. The trajectory of the hydrostatic normal compaction trend, therefore, depends on geothermal gradient and burial history. Let us consider the implications for normal compaction trends in general, when the vertical effective stress acting on a mudstone monotonically increases over time without the constraint that the pore pressure remains hydrostatic.

In the diagenetic regime, mudstone porosity can be reduced by purely chemical compaction with no increase in vertical effective stress. This behaviour is illustrated by the horizontal red trend in Fig. 2c, starting from an arbitrary point on the hydrostatic normal compaction trend, and would apply for a mudstone buried in a pressure regime where the pore pressure–depth profile is parallel to the lithostatic stress–depth profile. Such a mudstone would still be normally compacted because it has not experienced any unloading. There is a continuum of possible normal compaction curves in any well for the mudstones in the diagenetic regime. This continuum is a surface that passes through the horizontal red trend in Fig. 2c and the hydrostatic normal compaction trend, with an upper bound at the normal compaction trend for purely mechanical compaction and a horizontal lower bound at the minimum possible value of vertical effective stress where clay diagenesis might begin. Thus the normal compaction trend for diagenetically altered mudstones in a well does not necessarily correspond to the hydrostatic normal compaction trend, as implied by the common practices of estimating the normal compaction trend by downward extrapolation from the hydrostatically pressured shallow mudstones in the well or by adopting a hydrostatic normal compaction trend measured in an offset well.

Where the effects of porosity loss on density and sonic log responses remain in the same proportions regardless of whether compaction is chemical or mechanical, as implied in Fig. 2c, then the normal compaction surface is vertical and planar on the 3-D plot, and projects onto a straight line on the crossplot of sonic transit time versus density. That projection seems to be linear for illite-rich mudstones in the Haltenbanken wells, at temperatures above ~100 °C (Fig. 3). Whatever the shape of the normal compaction surface, there is an unloading curve corresponding to each point on that surface, as shown for unloading from the hydrostatic normal compaction trend in Fig. 2b, and there is a continuum of unloading curves forming an unloading volume in this 3-D space. Values of sonic transit time and density are not sufficient to determine vertical effective stress unambiguously on the normal compaction surface, nor inside the unloading volume, unless the specific normal compaction trend that applies for the mudstones in the subject well is known. Another variable is needed that accounts for the amount of clay diagenesis.

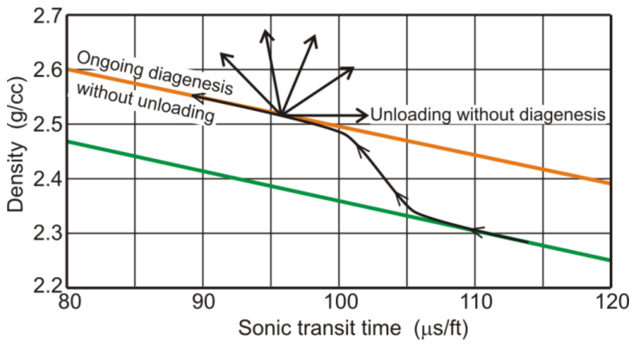

Fig. 3. Mudstone compaction trend (black arrowed curve) on a sonic–density crossplot based on results obtained by Dutta (2002) in the Gulf of Mexico. The trend is followed by a mudstone undergoing progressive burial and compaction without unloading. The lower (green) and upper (orange) lines are Dutta's trends for smectite-rich and illite-rich mudstones, respectively. The fan of arrows indicates possible depth trends for a diagenetically altered mudstone, ranging from ongoing diagenesis without unloading to unloading without diagenesis.

Clay diagenetic reactions are kinetic reactions that depend on temperature and time, so a time-temperature integral can be used to account for the amount of clay diagenesis (e.g., Dutta, 1986, 2016), assuming that detailed mineralogy is not available. In Fig. 2d, contours for the degree of diagenesis are shown schematically on the unloading surface, and they extend as surfaces into the unloading volume. Thus, in principle, the sonic transit time, density and diagenetic state are sufficient to determine the vertical effective stress. In practice, it is difficult to determine the normal compaction trend for the mudstones in a given well because it depends on the temperature history and maximum vertical effective stress experienced by the mudstones at each point in depth. Generally, in overpressured and diagenetically altered mudstones, the correct normal compaction trend is not the hydrostatic normal compaction trend.

3. Pore pressure estimation using Eaton's method

The most widely applied method of pore pressure estimation in mudstones over the past 40 years has probably been the empirical method of Eaton (1975) using the sonic log. We start by applying it to the mudstones of the Cretaceous Kvitnos and Lange formations at Haltenbanken to demonstrate where some more sophisticated approach is needed. In Eaton's method, the vertical effective stress, σ_v', is estimated from the measured sonic transit time, Δt, using the equation

$$\sigma_v'/\sigma_n' = (\Delta t_n/\Delta t)^3 \tag{1}$$

where σ_n' and Δt_n are the vertical effective stress and sonic transit time on the normal compaction curve for hydrostatic pore pressure at the depth of measurement.

A curious feature of Eaton's method is that Equation 1 implies the sonic velocity becomes zero in a mudstone at zero vertical effective stress, which is wrong. Nevertheless, the method is still popular because it is robust to apply for various reasons. Its simplicity in depending essentially on the sonic log is an advantage because the tool is compensated to cope with poor borehole conditions. Although some density information is required to estimate vertical effective stress over the range of interest, it is not a necessary requirement that a density log is available in the subject well. The sonic response is sensitive to the higher porosity retained where overpressure is due to disequilibrium compaction, and also to unloading overpressure that causes flexible connecting pores of high aspect ratio to open (Bowers and Katsube, 2002). The normal compaction curve for the sonic log is commonly developed by downward extrapolation into the overpressured zone, and there is some leeway to adjust empirically the extrapolated trend to fit pressure data in offset wells. As an alternative to empirical adjustment of the extrapolated hydrostatic normal compaction trend, the standard exponent of 3 for the ratio of sonic transit times in Equation 1 can be adjusted to fit data from offset wells, a procedure that has been called “cheatin’ with Eaton”.

Since the pressure–depth profile in the Kvitnos and Lange formations is very similar across Haltenbanken, approximately parallel to the lithostatic stress (Fig. 3 in Part 1), no well in the area has a sonic log that records the hydrostatic normal compaction trend. We selected well 6406/2-3 (Fig. 1) for application of Equation 1 to calculate the sonic normal compaction trend from the measured transit times and known values of vertical effective stress, so that it could be used in other Haltenbanken wells. Lithostatic stress was computed from the density log, and the vertical effective stress was obtained by subtracting pore pressure from the lithostatic stress at each depth step. Pore pressure was estimated by linear interpolation through the pressure measurements. The calculated sonic normal compaction trend is shown in Fig. 4 together with the results of using it on the same well. As expected because of the circularity in the procedure, the estimated pore pressures are a good fit to the measurements.

In Fig. 5 we show the results of applying Eaton’s method to the sonic logs in three other wells, located progressively further to the northeast (Fig. 1), using the sonic normal compaction trend obtained from well 6406/2-3. The result in well 6506/11-6, a nearby well in the Kristin Field, is good, as would be expected. In wells 6507/7-12 and 6507/2-3, however, the amount of overpressure is overestimated by ~50%. Considering the rather simple, lithostat-parallel, pressure regime across Haltenbanken (Fig. 3 in Part 1), the results for these two northeastern wells are poor.

A clue to the reason for the poor results lies in the density logs (Fig. 6). At any depth below seafloor, the smoothed density values are greater in wells 6507/7-12 and 6507/2-3 than in wells 6406/2-3 and 6506/11-6, which shows that the mudstones in the northeastern wells are more compacted. Analysis of the sonic–density crossplots for these four wells (Fig. 8 in Part 1) confirms that the mudstones in the northeastern wells have experienced greater vertical effective stress. The greater depths to the onset of unloading in the southwestern wells implies that they have retained more overpressure attributable to disequilibrium compaction, so at any given depth the mudstones have higher porosity than in the northeastern wells.

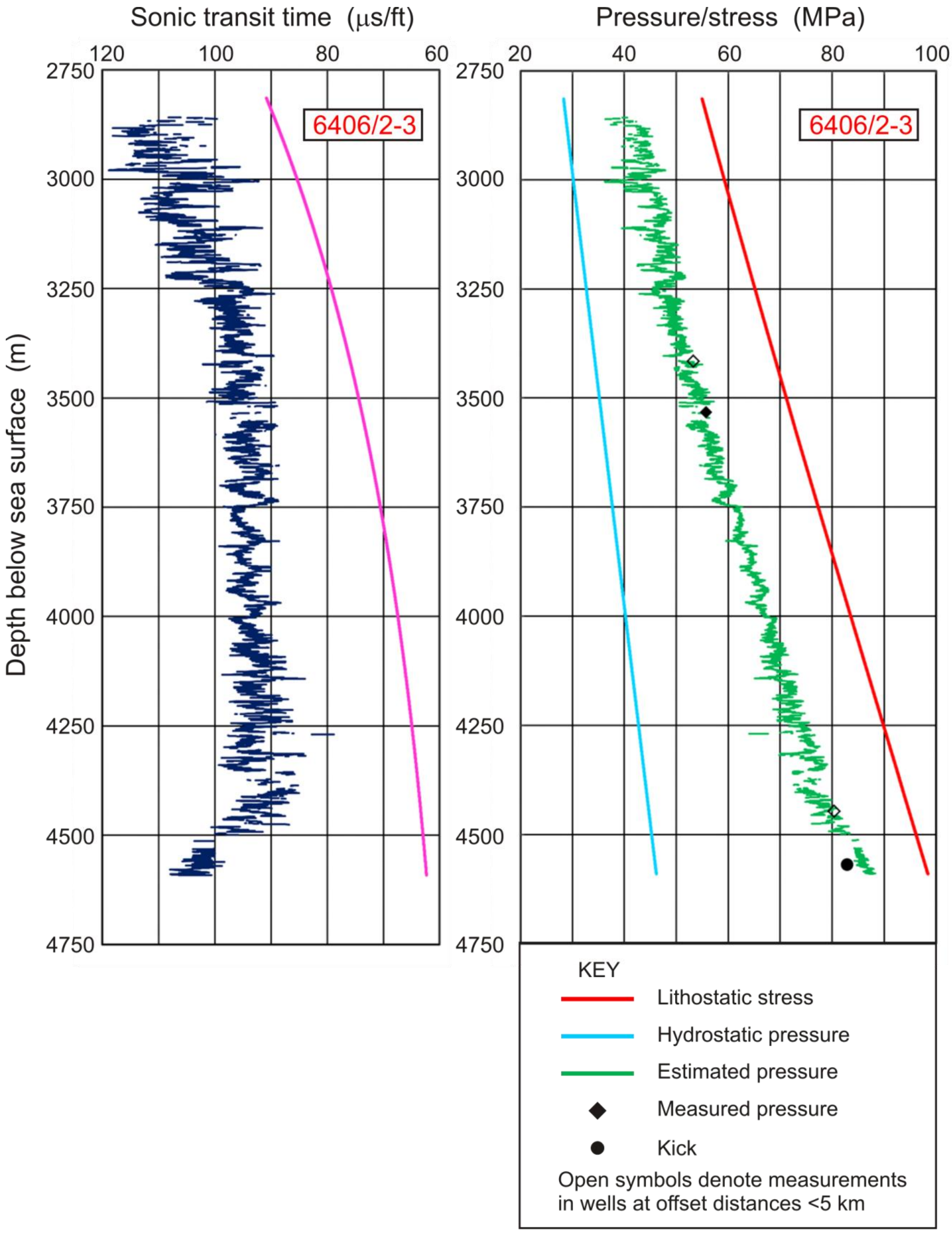

Fig. 4. Left: Sonic log through Kvitnos and Lange formations after editing to select mudstone data points, with the normal compaction trend (magenta) derived to fit pressure measurements using Eaton's method for the sonic log (Equation 1). Right: Pressure measurements and pressure–depth profile calculated by Equation 1 from the sonic log and normal compaction trend on the left.

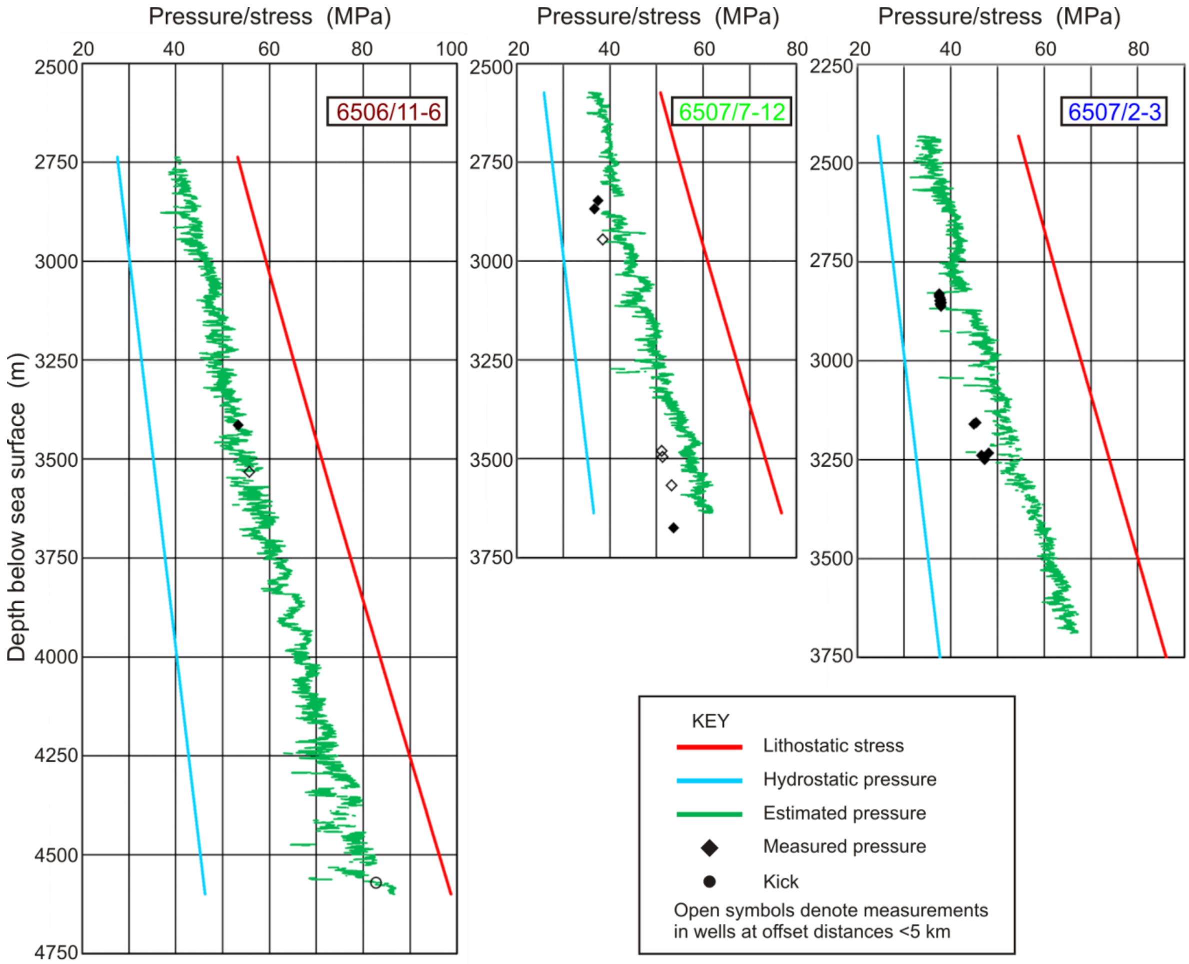

Fig. 5. Pressure measurements and pressure–depth profiles calculated by Equation 1 from the sonic logs in wells 6506/11-6, 6507/7-12 and 6507/2-3, using the sonic normal compaction trend obtained from well 6406/2-3.

As a practical matter, when drilling an exploration well in a mature basin the normal compaction trend should be estimated from the nearest neighbouring wells. If the normal compaction trend had been estimated in well 6507/7-12 for application of Eaton's method to well 6507/2-3, or vice versa, pressure estimates would have been much more accurate. However, our ultimate objective is to develop improved methodology for application at any stage of exploration activity, including exploration in frontier basins.

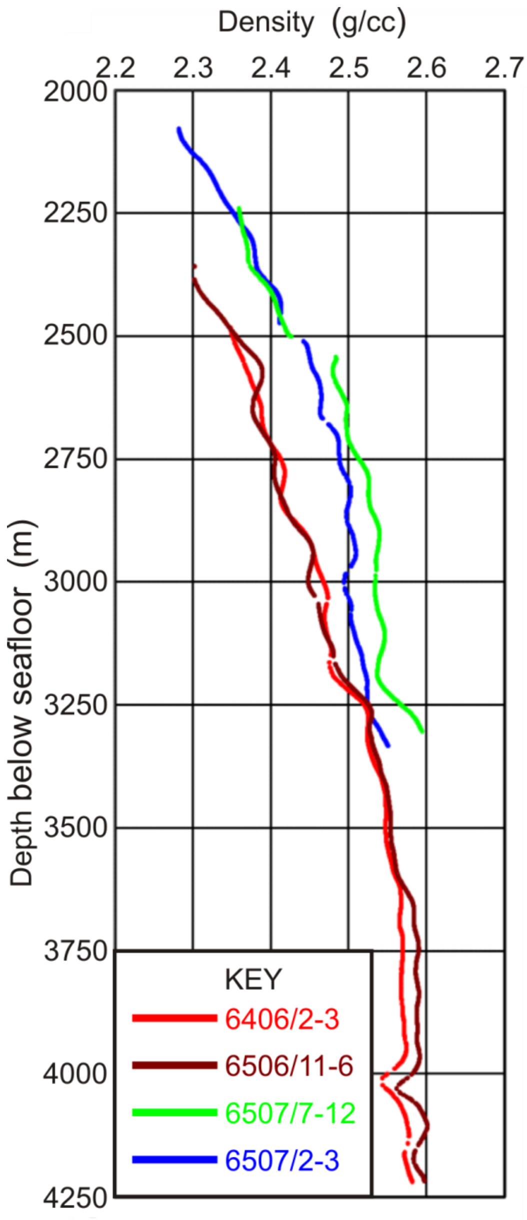

Fig. 6. Density logs, following selection of mudstone data points and smoothing, through the Cretaceous Kvitnos and Lange formations in four wells. The colour key matches the labels for well locations Fig. 2.

4. Two-step methods of pore pressure estimation

As argued above, it is not possible to define a unique normal compaction trend for porosity, or any porosity proxy, in terms of vertical effective stress for mudstones in the diagenetic regime because there are both mechanical and chemical contributions to compaction. Diagenetically altered mudstones continue to compact mechanically in response to increasing effective stress; and clay diagenesis, the cause of chemical compaction, reduces the porosity in a mudstone held at constant effective stress. Nevertheless, a unique normal compaction trend that lies somewhere in the normal compaction surface (Fig. 2d) exists for the mudstones in any well to describe the variation in their density and sonic transit time with diagenetic state and vertical effective stress if they are not unloaded. If we assume that unloading does not affect the density response, therefore, the density log gives an estimate of the maximum vertical effective stress experienced, and hence of the amount of overpressure due to disequilibrium compaction, provided that this unique normal compaction trend is known. The sonic log response could then be incorporated to estimate the amount of overpressure due to unloading.

For mudstones in the mechanical compaction regime, the method proposed by Bowers (2001) is a two-step method, even though it may be concatenated into a single step to calculate the total overpressure because it is assumed that the vertical effective stress acting on a mudstone is uniquely defined by the combination of density and sonic transit time, without regard to its diagenetic state (Fig. 2b). However, Bowers' (2001) method is simplistic for application in diagenetically altered mudstones in that it assumes that unloading has taken place from the point on the hydrostatic normal compaction trend (Fig. 2b) corresponding to the maximum vertical effective stress experienced by the mudstone.

There are practical problems in trying to implement the two-step method for diagenetically altered mudstones. The principal difficulty is in establishing the first of the three empirical relationships required in each well over the depth range of interest: the relationship between density and the maximum vertical effective stress experienced by the mudstones. In addition, we require the relationship between sonic transit time and density at maximum vertical effective stress, which we suggest corresponds to Dutta's trend for illite-rich mudstones without unloading (Fig. 3), and the unloading relationship between sonic transit time and vertical effective stress. The first two relationships define where the normal compaction trend for the mudstones in each well lies in the normal compaction surface (Fig. 2d). These three relationships suffice if we may assume that the effect of unloading on the density log response is negligible.

4.1. Budge-Fudge approach

The Budge-Fudge approach of Sargent et al. (2015) offers a partial solution to the difficulties in applying the two-step method to pore pressure estimation in diagenetically altered mudstones, and could be a starting point for a completely deterministic two-step solution using density and sonic logs. The method is applicable to mudstones at temperatures above 100 °C, and makes use of the crossplot between sonic transit time and density (Fig. 3). The first section of the curve at bottom right corresponds to the mechanical compaction stage; the steep middle section corresponds to the main stage of illitization of smectite at temperatures in the range ~70–100 °C; and the third section of the curve corresponds to ongoing chemical and mechanical compaction at temperatures above ~100 °C.

An assumption underlying the Budge-Fudge approach is that there is a unique sonic–density trend for mudstones of a given lithology at temperatures above ~100 °C, provided they are not unloaded. The unique trend is the late-stage sonic–density compaction trend of Dutta (2002) for illite-rich mudstones, the upper straight line in Fig. 3 labelled "ongoing diagenesis without unloading", with empirical adjustment of the intercept. This assumption permits estimation of the amount of unloading overpressure present in the mudstones (Sargent et al., 2015). The limitation is that the maximum effective stress experienced by the mudstones has to be estimated from all available information, possibly including basin modelling, because we do not have a priori information to estimate the values of maximum effective stress experienced from the density log and so estimate the contribution to overpressure from disequilibrium compaction.

Application of the Budge-Fudge approach to well 6406/2-3 is illustrated in Fig. 7. Density and sonic logs (Fig. 7a and b) were edited to remove spikes and poor sections, e.g., around casing points, and mudstone data points in the Kvitnos and Lange formations were selected using the natural gamma log as a discriminant. Lithological corrections have been applied to the sonic log to reduce scatter, based on short-wavelength correlations between the natural gamma log and the difference between neutron porosity and density porosity, as described in Part 1. The cubic function that best fits the density data is shown in cyan on Fig. 7a.

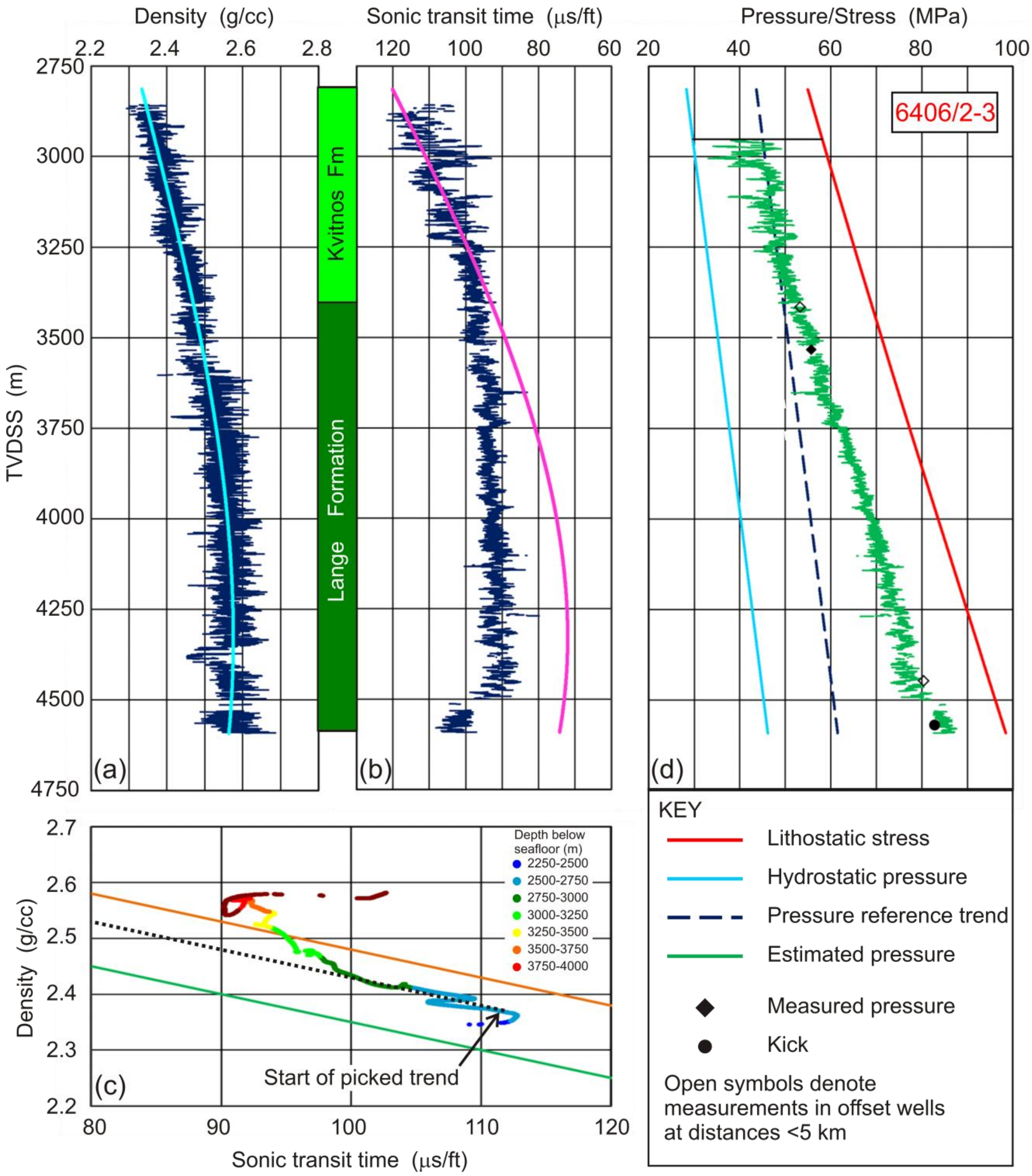

Fig. 7. Application of the Budge-Fudge method to mudstones of the Kvitnos and Lange formations in well 6406/2-3. (a) Density log with best-fitting cubic trend. (b) Lithology-corrected sonic log with sonic reference trend. (c) Sonic–density crossplot with picked compaction trend for illite-rich mudstones that have not been unloaded (black dotted line). The best-fitting density curve in (a) is used to obtain the sonic reference trend in (b) by combining it with the dotted trend picked on the data in (c). The green and orange lines are Dutta's (2002) trends for smectite-rich and illite-rich mudstones, respectively. (d) Pressure/stress–depth plot with key, showing pressure measurements, the pressure reference trend and the estimated pore pressure. The water depth is 372 m.

The next step in the analysis makes use of the sonic–density crossplot (Fig. 7c), for which the log data were smoothed using a Hanning window of length 100 m. The geothermal gradient in this well is ~38 ^{0}C km^{-1}, so the temperature at the top of the Kvitnos Formation is approximately 95 ^{0}C. Compared to the analysis shown by Sargent et al. (2015), the trends on the crossplots for all wells are more consistent as a result of applying the lithological corrections to the sonic log. From a point shortly below the top of the Kvitnos Formation in this well, the data track a linear trend. Although some switchback behaviour occurs between 109 μs ft^{-1} and 105 μs ft^{-1}, which we attribute to residual lithological variations, the linear nature of the trend is quite well defined and we interpret it as the compaction trend for illite-rich mudstones. Accordingly, we pick a trend line for these data in the form

$$\Delta t = \Delta t_0 - 200\rho, \qquad (2)$$

where Δt is sonic transit time in units of μs ft^{-1} and ρ is density in units of g cm^{-3}. The gradient is fixed at 200 with these log units, and the value of Δt_0 is determined from Equation 2 using the picked values of sonic transit time and density at the starting point, marked on Fig. 7c.

The best-fitting curve for the density data is then combined with Equation 2 to yield the "sonic reference trend" plotted in magenta on Fig. 7b. We emphasize that the sonic reference trend is not the hydrostatic normal compaction trend, as used, for example, in the method of Eaton (1975), because it is not, in general, the same sonic–depth trend that the sonic log would follow in the case of hydrostatic pore pressure. The sonic reference trend is the expected trend of the sonic log, given the density log, which would be followed by illite-rich mudstones if they were presently at the maximum vertical effective stress they had previously experienced. Deviation of the real sonic log data to higher transit times than the sonic reference trend is attributed to unloading.

The next step is to estimate the maximum vertical effective stress previously experienced by the illite-rich mudstones, and subtract it from the lithostatic stress to give the "pressure reference trend" (Fig. 7d). We made an initial guess for the pressure reference trend based on knowledge of basin history. We are fairly confident from the burial history that pore pressure in the Cretaceous formations was close to hydrostatic at 2.8 Ma, immediately prior to deposition of the glaciogenic sediments of the Naust Formation. Given that Naust burial was rapid, the initial guess of the pressure reference trend at all depths was that it equals the hydrostatic pressure plus a "budge" given by the vertical effective stress at the base of the Naust Formation. This initial guess would be correct if the additional vertical stress due to deposition of the Naust Formation is borne entirely by the pore fluid in the Cretaceous mudstones. For well 6406/2-3, the initial budge was a constant value of 12.9 MPa, calculated from the densities of the Naust Formation and seawater, over the full depth range occupied by the Kvitnos and Lange formations. We then adjusted the budge in combination with the final step, described in the next paragraph, to fit the pressure measurements in the well. This adjustment is a purely empirical, data-driven operation, so we call it "fudging the budge". The final value of the budge was 15.4 MPa at all depths, giving a pressure reference trend parallel to the hydrostatic pressure (Fig. 7d).

The amount of overpressure due to unloading was estimated from the sonic log and the sonic reference trend using the unloading relation between vertical effective stress σ_v' and sonic velocity V in units of ft s^{-1} (cf. Bowers, 1995):

$$\sigma_v'/\sigma_R' = [(V - 5000)/(V_R - 5000)]^U, \quad (3)$$

where σ_R' is the difference between lithostatic stress and reference pressure, and V_R is velocity on the sonic reference trend. The value 1.8 was found empirically for the unloading exponent U. The resulting estimated pore pressure trend (Fig. 7d) matches quite well one direct pressure measurement in this well, a second pressure value estimated from a kick, and two pressure measurements in offset wells.

The revised Budge-Fudge results for wells 6506/11-6, 6507/7-12 and 6507/2-3 are shown in Figs 8, 9 and 10, respectively. The value of 1.8 was retained for the unloading exponent U. The values of the initial budge applied, the final budge estimate, and the mudstone porosity at 2700 m depth below seafloor in each well are shown in Table 1. The final budge values applied are our

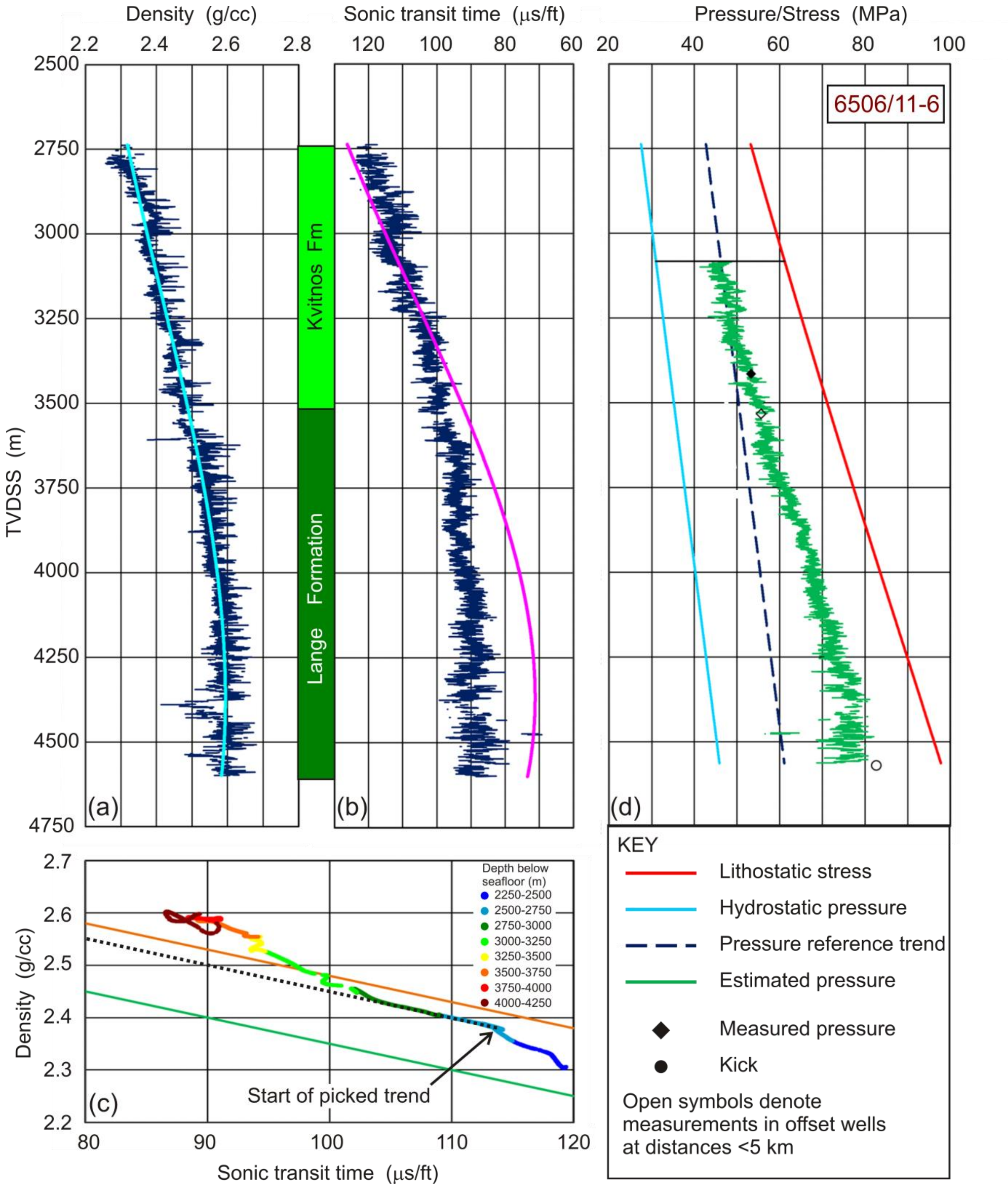

Fig. 8. Application of the Budge-Fudge method to mudstones of the Kvitnos and Lange formations in well 6506/11-6. (a) Density log with best-fitting cubic trend. (b) Lithology-corrected sonic log with sonic reference trend. (c) Sonic–density crossplot with picked compaction trend for illite-rich mudstones that have not been unloaded (black dotted line). The best-fitting density curve in (a) is used to obtain the sonic reference trend in (b) by combining it with the dotted trend picked on the data in (c). The green and orange lines are Dutta's (2002) trends for smectite-rich and illite-rich mudstones, respectively. (d) Pressure/stress–depth plot with key, showing pressure measurements, the pressure reference trend and the estimated pore pressure. The water depth is 380 m.

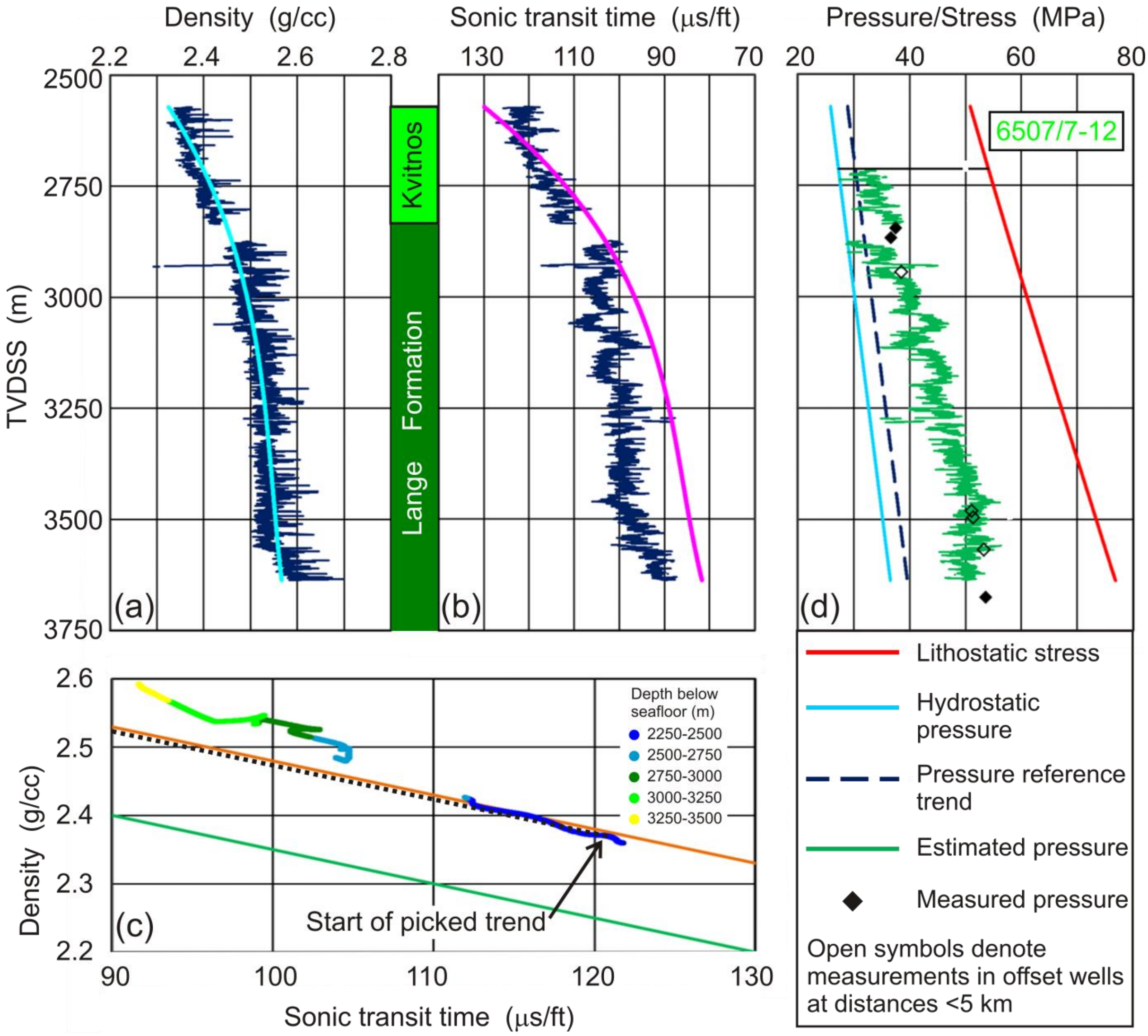

Fig. 9. Application of the Budge-Fudge method to mudstones of the Kvitnos and Lange formations in well 6507/7-12. (a) Density log with best-fitting cubic trend. (b) Lithology-corrected sonic log with sonic reference trend. (c) Sonic–density crossplot with picked compaction trend for illite-rich mudstones that have not been unloaded (black dotted line). The best-fitting density curve in (a) is used to obtain the sonic reference trend in (b) by combining it with the dotted trend picked on the data in (c). The green and orange lines are Dutta's (2002) trends for smectite-rich and illite-rich mudstones, respectively. (d) Pressure/stress–depth plot with key, showing pressure measurements, the pressure reference trend and the estimated pore pressure. The water depth is 333 m.

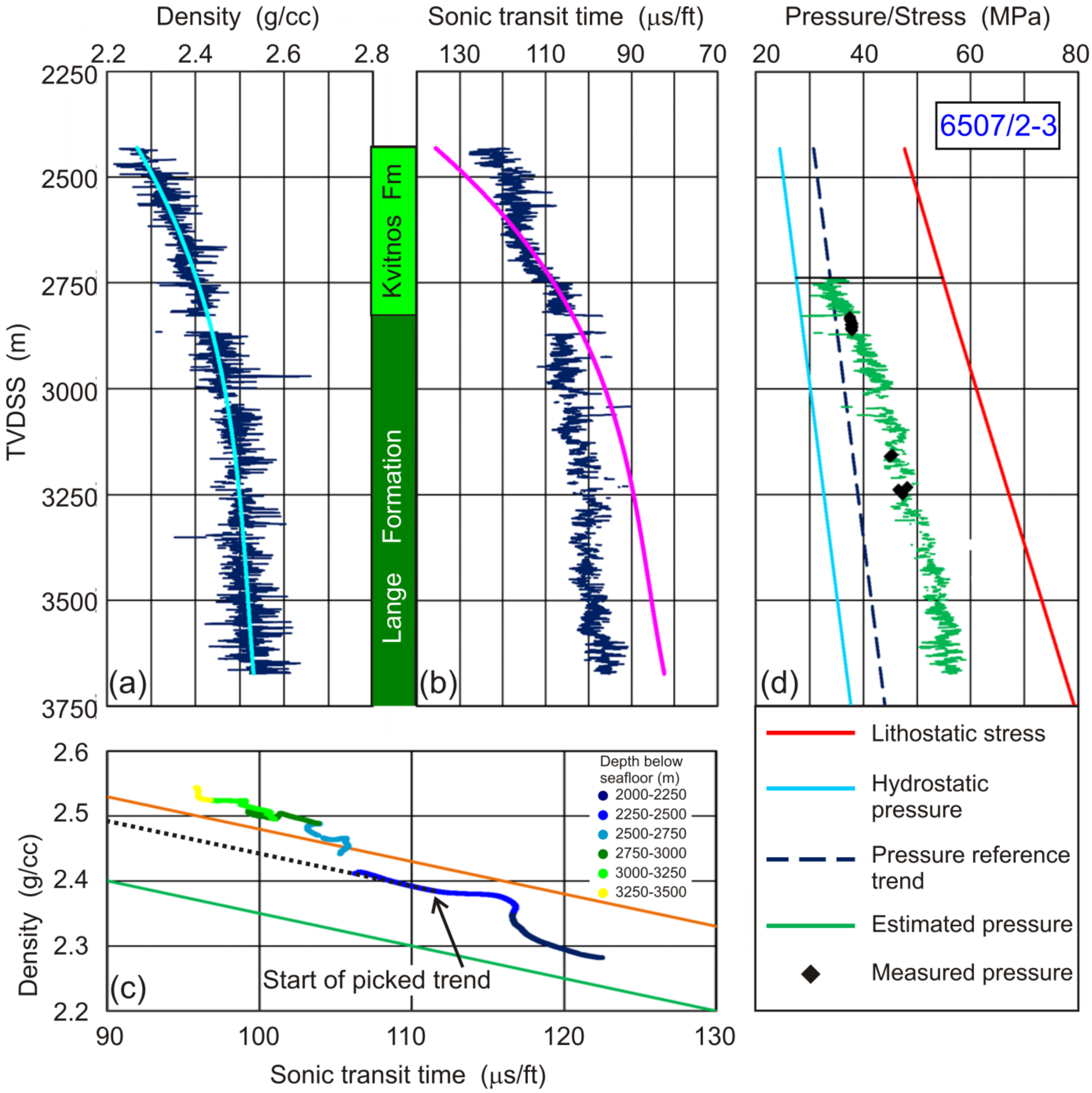

Fig. 10. Application of the Budge-Fudge method to mudstones of the Kvitnos and Lange formations in well 6507/2-3. (a) Density log with best-fitting cubic trend. (b) Lithology-corrected sonic log with sonic reference trend. (c) Sonic–density crossplot with picked compaction trend for illite-rich mudstones that have not been unloaded (black dotted line). The best-fitting density curve in (a) is used to obtain the sonic reference trend in (b) by combining it with the dotted trend picked on the data in (c). The green and orange lines are Dutta's (2002) trends for smectite-rich and illite-rich mudstones, respectively. (d) Pressure/stress–depth plot with key, showing pressure measurements, the pressure reference trend and the estimated pore pressure. The water depth is 356 m.

Well number	Initial budge guestimate (MPa)	Final budge applied (MPa)	Mudstone porosity at 2700 mbsf (%)
6406/2-3	12.9	15.4	19.8
6506/11-6	12.7	15.2	20.3
6507/7-12	13.0	3.0	15.5
6507/2-3	11.3	6.3	17.2

Table 1. Initial budge guestimate and final budge applied to obtain the pressure reference trend and Cretaceous mudstone porosity at 2700 m below seafloor for each of the four Haltenbanken wells. In calculating mudstone porosity from smoothed density logs, the fluid density was assumed to be 1.05 g cm^{-3} and the grain density to be 2.75 g cm^{-3}.

estimates of the amount of overpressure in each well attributable to disequilibrium compaction. Broadly, they correlate with the mudstone porosity values.

In near-neighbour wells 6406/2-3 and 6506/11-6, the final budge applied was 2.5 MPa greater than the vertical effective stress at the base of the Naust Formation, which equals the maximum possible amount of disequilibrium compaction overpressure due to Naust burial. The implication is that at least 2.5 MPa of overpressure was present in the Cretaceous mudstones immediately prior to Naust burial. The numbers in this analysis differ from those given by Sargent et al. (2015) as a consequence of the lithological corrections applied to the sonic log. In wells 6507/7-12 and 6507/2-3, the final budge applied is less than the vertical effective stress at the base of the Naust Formation, which suggests that some leakage of fluid took place during Naust burial, allowing the vertical effective stress to increase temporarily. Subsequently, ongoing clay diagenesis in all four wells reduced permeability and generated additional unloading overpressure.

5. Conclusions

The normal compaction trends for diagenetically altered mudstones depend on their temperature history and the maximum effective stress experienced. Although there is a unique hydrostatic normal compaction trend in any well for mudstones of given initial lithology that have been uniaxially consolidated, the true normal compaction trends relating porosity and porosity proxies such as density and sonic transit time to vertical effective stress vary according to the maximum vertical effective stress experienced. Consequently, the vertical effective stress in a diagenetically altered mudstone is not uniquely defined by sonic transit time and density unless the true normal compaction trend and its associated unloading surface are known.

Eaton's (1975) method of pore pressure estimation using the sonic log produced poor results in some of the Cretaceous mudstones at Haltenbanken when we estimated the hydrostatic normal compaction trend from the data in a single well. We suggest the reason is because the sonic log responds differently to overpressure generated by disequilibrium compaction and by unloading. A better approach is to estimate the two contributions to overpressure separately, using some kind of two-step method. Of course, Eaton's (1975) method would work better if the hydrostatic normal compaction trend was always estimated from a near-neighbour well.

Cicchino et al. (2015) deduced that the Cretaceous mudstone porosity variations at Haltenbanken are due to variable water escape following rapid burial by the glaciogenic sediments of the Naust Formation, with water escape being more inhibited from the higher porosity mudstones in the SW of the study area (Fig. 1) because of their distal setting. That conclusion is corroborated by the results of the Budge-Fudge analysis: the wireline log responses show that the lower porosity mudstones in the northeastern wells have been subjected to greater vertical effective stress than the higher porosity mudstones in the southwestern wells at the same depths.

The Budge-Fudge approach is a partial solution to the problem of estimating pore pressure in diagenetically altered mudstones that copes with unknown normal compaction trends for density and sonic transit time. It also allows for unknown lithological effects on density logs by empirically fitting the intercept in Equation 2 to the data. However, it does depend on the assumption that there is a unique sonic–density trend for diagenetically altered mudstones above ~100 °C that have not been unloaded, even though vertical effective stress is not uniquely defined by density and sonic transit time unless the diagenetic state is also known. Maximum effective stress is best estimated from all available information, including offset wells, with basin modelling where appropriate.

The Budge-Fudge approach as applied here is a form of post-drill analysis, and would need modification if it were to be applied while drilling. Smoothing of the density and sonic logs could only be done over the logged depth range while drilling, potentially making it more difficult to identify accurately the sonic–density trend for illite-rich mudstones that have not been unloaded and the sonic reference trend. The value of the unloading exponent U in Equation 3 would have to be assumed in advance of drilling; however, results from the Cretaceous mudstones at Haltenbanken suggest that the value found empirically in offset wells may be appropriate. This approach needs to be tested in other basins where mudstone lithology is laterally consistent and pressure–depth profiles exhibit strong lateral variation.

For a more comprehensive implementation of the two-step method for estimating pore pressure in diagenetically altered mudstones and for modelling their compaction correctly, the empirical relationships described in section 4 need to be established. With reference to Fig. 2, they amount to knowing the normal compaction trend over the depth range of interest for the given depositional lithology, present diagenetic state, and maximum vertical effective stress experienced, and knowing the unloading relationship between sonic transit time and vertical effective stress. Application of the Budge-Fudge approach to offset wells could be useful for estimating the normal compaction trend for mudstones in a subject well at the maximum effective stress they have experienced, and so form the basis of the full two-step method using the density and sonic logs. Our initial efforts to implement the full two-step method in this way at Haltenbanken have produced inconsistent results with fluctuations in estimated pore pressure reflecting some of the fluctuations in the density logs. We suspect that variations in the mineralogical composition of the mudstones are responsible. The procedure needs to be tested in other basins where mudstone lithology is laterally consistent. Desirable additional developments include systematic checking of the calibration of density logging tools and of the corrections applied, addressing the uncertainty in mudstone lithology, inclusion of the 3D stress tensor, and implementing a Bayesian methodology for estimating uncertainties.

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